Fate of permafrost in Denali National Park and Preserve - A modeling investigation

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Outline

- Permafrost and Active-layer
- Permafrost in Denali National Park and Preserve (DENA)
- Permafrost model (GIPL 1.0)
  - Salient features
  - Limitations
  - Input data
  - Output products
- Modeling results
  - Accuracy assessment
- Summary
Permafrost

Ground (soil or rock and included ice and organic matter) that remains at or below 0 °C for at least two consecutive years, for natural climatic reasons (van Everdingen, 1998).

Left: U.S. Army Permafrost Tunnel at Fox, Fairbanks
Right: Ice-rich permafrost near Toolik Field Station, Alaska

Photo Courtesy: M. Gooseff
Active layer

The layer of the ground above permafrost that thaws in summer and freezes again in winter (Muller, 1947).

William and Smith (1989)
DENA Permafrost
Location of DENA in Alaska
Why care about DENA permafrost?

“Permafrost is an important driver of Denali’s ecosystems because thermal characteristics of the ground directly control or indirectly influence Denali’s local hydrology, pattern of vegetation, and wildlife communities”. (Adema, 2006)

- Permafrost as foundation
- State of permafrost
- Form and amount of ice

Wigand Creek thermokarst developed by thawing of ice-wedge polygons, Toklat Basin, DENA (Adema, 2006)
Thermokarsts, Toklat Basin, DENA

(a-b) Wigand Creek Thermokarst
(c-d) Boundary Thermokarst
(e-f) Hook’s Hole Thermokarst

Yocum et al. (2006)
A generalized permafrost map of DENA

A product of the joint NPS-NRCS six year soils survey of DENA (Clark and Duffy, 2006)

(>80% of the soil) **Continuous**
(20 - 80%) **Discontinuous**
(5-20%) **Sporadic**

Nearly **45% of the park** underlain by continuous or discontinuous permafrost

**32% Not rated**

**1375 Sites in 16,676 km² area**
Or **1 site per 12 km²**
Modeling

1. Permafrost presence or absence
2. State of permafrost
3. Can be improved
Permafrost model GIPL 1.0
GIPL 1.0 model salient features

- Models near-surface permafrost
- An equilibrium model (temperature at the bottom of seasonal freeze-thaw layer and its thickness)
- Conductive heat transfer
- Analytical solution of the ground heat equation that includes freezing/thawing processes (Kudryavtsev et al. 1974; Romanovsky and Osterkamp 1997)
- Accounts for the effects of snow cover, surface vegetation, soil moisture and soil thermal properties
- Ignores the effect of geothermal heat flux
GIPL 1.0 model limitations

• Assumes
  – Steady state temperature regime (annual or decadal cycle)
  – No within layer variation in thermal properties
  – No change in surface vegetation

• Does not take into account
  – Unfrozen water content
  – Effect of wind on snow distribution (thickness)
GIPL 1.0 model conceptual diagram

(Marchenko and Romanovsky, 2012)
Input Data

- **Climate data (mean monthly air temperature and monthly total precipitation)**
  - CRU Climate data (1901-2009); Decades: 1950-59, 2000-09
  - 5-GCM composite A1B Scenario (2001-2100); Decades: 2001-10, 2051-60, 2091-2100

- **Ecosystem Properties**
  - **Snow Map**: Nine snow classes (Marchenko, unpublished)
    - Fresh snow density and maximum snow density
  - **Ecotype Map**: Twenty Ecotypes (Stevens et al, 2001)
    - Surface vegetation thickness
    - Thermal diffusivity in frozen and thawed state
  - **Soil Map**: One-Hundred-and-Fifty-One soil classes (Clark and Duffy, 2006)
    - Volumetric heat capacity in frozen and thawed state
    - Thermal conductivity in frozen and thawed state
    - Volumetric water content
Output products

• Average temperature @
  – ground surface
  – soil surface
  – bottom of seasonal freeze-thaw layer

• Thermal offset

• Thickness of seasonal freeze-thaw layer

• Thickness of snow cover

Input resolution = Output resolution
Input maps for DENA permafrost modeling
Mean Decadal (2000-09) Air Temperature Map
Denali National Park and Preserve

CRU Mean 2000-09
Air Temp. (C)
High : +3.1
Low : -29.3
Water Bodies
Hillshade Model
High
Low
Mean Decadal (2000-09) Air Temperature Map
Denali National Park and Preserve

Input
Decadal Mean Annual Precipitation
CRU 2000-09
Snow Map
Denali National Park and Preserve

DENA Snow Classes
- Alpine
- Bare surface
- Conifer forest
- Grassland
- Inland water
- Mixed forest
- Mixed shrub
- Shrub deciduous
- Upland tundra
Ecotype Map
Stevens et al. (2001)

Derived from Landsat images

28 m Spatial resolution
Permafrost modeling results
Climate input:
Decadal mean air temp.: -1.6 °C
Decadal mean annual precip.: 651 mm

Modeled permafrost characteristics:
Near-surface Permafrost @ 51% of DENA
Mean decadal permafrost temp.: -1.1 °C
Climate input:
- Decadal mean air temp.: -1.6 °C
- Decadal mean annual precip.: 651 mm

Modeled active-layer characteristics:
- Mean Decadal ALT: 1.1 m
- Active-Layer Thickness < 1 m: 19%
Products accuracy assessment
Warm-bias Test
CRU 2000-09 forcing

Clark and Duffy (2006)

Permafrost present at 408 Sites
Agree (88%)
Disagree (12%)

Modeled Present Field Present
Present
Absent Present

Possible reasons of disagreement:
- Scale
- Model limitations
Clark and Duffy (2006)

Permafrost absent at 967 Sites
Agree (84%)
Disagree (16%)

Possible reasons of disagreement:
- Scale
- Model limitations

Cold-bias Test
CRU 2000-09 forcing

Modeled Permafrost Map (Decade 2000)
Denali National Park and Preserve

Modeled Permafrost
- Present
- Absent
- Water Bodies

Hillshade Model
- High
- Low

Present Absent
Absent Absent

Permafrost absent at 967 Sites
Agree (84%)
Disagree (16%)
## Comparison with recorded ground temperature

<table>
<thead>
<tr>
<th>Recorded at climate stations</th>
<th>Dunkle Hills</th>
<th>Stampede</th>
<th>Toklat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average air temperature</td>
<td>-2.8 °C</td>
<td>-4.1 °C</td>
<td>-3.1 °C</td>
</tr>
<tr>
<td>Average ground temperature at 0.02 m</td>
<td>1.1 °C</td>
<td>0.4 °C</td>
<td>1.0 °C</td>
</tr>
</tbody>
</table>

### CRU average air temperature (2000-09)

-1.8 °C | -1.6 °C | -1.4 °C

### Modeled (2000-09)

<table>
<thead>
<tr>
<th>Average ground surface temperature</th>
<th>0.3 °C</th>
<th>0.9 °C</th>
<th>0.6 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ground temperature at the bottom of seasonal freeze-thaw layer</td>
<td>0.1 °C @ 0.75 m</td>
<td>-0.6 °C @ 1.12 m</td>
<td>0.1 °C @ 1.0 m</td>
</tr>
</tbody>
</table>

Smaller (< 1 °C) differences between modeled ground surface temperatures and recorded ground temperatures (at 0.02 m)
Modeled permafrost maps with past climate forcing
Climate input:
Decadal mean air temp.: -3.5 °C
Decadal mean annual precip.: 679 mm

Modeled permafrost characteristics:
Near-surface permafrost @ 75% of DENA
Mean decadal permafrost temp.: -2.1 °C

Permafrost Map
CRU 1950-59 forcing

Ground temperature at the bottom of seasonal freeze-thaw layer
Climate input:
Decadal mean air temp.: -3.5 °C
Decadal mean annual precip.: 679 mm

Modeled permafrost characteristics:
Mean Decadal ALT: 1.1 m
Active-Layer Thickness < 1 m: 38%
Modeled permafrost maps with future climate forcing
Climate input:
Decadal mean air temp. : -0.7 °C
Decadal mean annual precip. : 845 mm

Modeled permafrost characteristics:
Near-surface permafrost @ 6% of DENA
Mean decadal permafrost temp. : -1.3 °C

Ground temperature at the bottom of seasonal freeze-thaw layer

Permafrost Map
5-GCM 2051-60 forcing
Climate input:
Decadal mean air temp.: +2.7 °C
Decadal mean annual precip.: 938 mm

Modeled permafrost characteristics:
Near-surface permafrost @ 1% of DENA
Mean decadal permafrost temp.: -3.3 °C

Ground temperature at the bottom of seasonal freeze-thaw layer
Climate input:
Decadal mean air temp.: -0.7 °C
Decadal mean annual precip.: 845 mm

Modeled active-layer characteristics:
Mean Decadal ALT: 1.1 m
Active-Layer Thickness < 1 m: 2 %
Climate input:
Decadal mean air temp.: +2.7 °C
Decadal mean annual precip.: 938 mm

Modeled active-layer characteristics:
Mean Decadal ALT: 0.8 m
Active-Layer Thickness < 1 m: 0.7 %
Near-surface permafrost (% of DENA area)

Decadal Mean Air Temperature (°C)

Decadal Mean Annual Precipitation (mm)
Summary

✔ Improved high-resolution (28 m) permafrost maps
✔ 86% agreement with field observations
✔ Smaller (< 1 °C) differences between modeled and recorded ground temperatures
✔ Scale and model limitations
✔ Near-surface ‘stable’ permafrost distribution is predicted to decline from present 51% of DENA area to a mere 6% by 2050s and to 1% by 2090s
✔ Only tiny areas of bedrock terrain at highest elevations are predicted to maintain ‘stable’ permafrost
Broader impacts

- How permafrost distribution may evolve in response to changing climate?
- Identify sites with higher risk of permafrost thawing
- Enable informed decision making
References

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http://permafrost.gi.alaska.edu/project/permafrost-modeling-alaskan-national-park-lands
Thank you for your time and attention.
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<tr>
<th>Climate characteristics</th>
<th>1950-59</th>
<th>2000-09</th>
<th>2051-60</th>
<th>2091-00</th>
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</thead>
<tbody>
<tr>
<td>Mean decadal air temperature (°C)</td>
<td>-3.5</td>
<td>-1.6</td>
<td>-0.7</td>
<td>+2.7</td>
</tr>
<tr>
<td>Mean decadal precipitation (mm)</td>
<td>679</td>
<td>651</td>
<td>845</td>
<td>938</td>
</tr>
</tbody>
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</tr>
</thead>
<tbody>
<tr>
<td>Permafrost distribution (%)</td>
<td>75</td>
<td>51</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Mean decadal permafrost temperature (°C)</td>
<td>-2.1</td>
<td>-1.1</td>
<td>-1.3</td>
<td>-3.3</td>
</tr>
<tr>
<td>Mean decadal active-layer thickness (m)</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>0.8</td>
</tr>
</tbody>
</table>